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1977 R C HOUTS, B P HOLT DAAG29-76-G-0212

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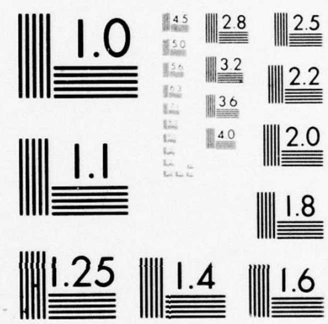
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DESIGN OF BANDSTOP DIGITAL FILTERS FOR REJECTING WEATHER OR CHAFF CLUTTER IN MTI RADARS*

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Abstract

A technique is described for designing FIR bandstop digital filters which effectively attenuate wideband clutter in a digital MTI radar processor. The clutter return can be caused by rain or chaff and is modeled with a Gaussian power-density spectrum. The bandstop filter is designed to minimize the transition region for fixed filter length, specified stopband width, stopband attenuation and passband ripple.

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Background

The primary interference to a radar signal return is called clutter. This clutter is typically much stronger than the narrowband doppler-shifted target return and may be caused by ground reflections, rainstorms or deliberate interference such as chaff. The ground clutter is effectively removed by a simple two or three tap digital filter in the moving-target indicator (MTI) radar signal processor. The degree to which the signal/clutter ratio is enhanced by the MTI filter is called the improvement factor (I). The standard definition of I assumes that the signal gain is computed by averaging over the entire filter response from dc to the pulse repetition frequency (1/T) where T is the pulse repetition or filter sampling interval. In point of fact, the frequency response of the two or three pulse canceller (TPC) is quite dependent upon frequency and provides a true gain over a restricted portion of the region and severe loss over much of the remaining response. However, the average signal gain is close to 0 dB; hence, I is really a measure of clutter loss (C) which can be more than 50 dB for a TPC and ground clutter. A study of the tradeoff between ground clutter rejection and usable passband with more sophisticated filters (N > 3) has been reported by Houts & Burlage [1].

Unfortunately, wideband clutter rejection requires a more sophisticated filter design because the average velocity (v_c) of the clutter spectrum is not zero and has a standard deviation (σ_v) which is much greater than the ground clutter value. Typically [2], for ground clutter $\sigma_v < 0.25$ m/s with $v_c = 0$, whereas for rain $1.0 < \sigma_v < 3.5$ m/s and chaff has $1.0 < \sigma_v < 2$ m/s with $v_c < 40$ m/s.

The considerable spread in σ_v is due to two facts. First, σ_v is primarily composed of two independent components, a turbulence component (σ_t) and a shear component (σ_s) which are sum-squared to form σ_v^2; second, σ_s is a function of range, whereas σ_t is ≈ 1.0 m/s independent of range. Translated to C-band radar ($f_t = 5.5$ GHz) this implies the clutter spectrum has a center frequency (f_c) between dc and 1.5 kHz and a standard deviation (σ) between 37 Hz and 128 Hz. In the presentations which follow, the frequency response will be normalized with respect to the sampling rate (1/T). Since finite-impulse response (FIR) digital filters have an amplitude response $|H(f)|$ which is symmetric with respect to 1/2T, a normalized frequency, F = fT ranging between 0 and 0.5 is sufficient to completely describe the filter response.

FIR Filter Design

The optimum, in a Chebyshev sense (minimized maximum error), FIR digital filter algorithm of McClellan et. al. [3] serves as the basis for designing a bandstop digital MTI filter. Intuitively, the ideal bandstop filter would be designed by specifying the desired stopband center frequency (f_s), bandwidth (B_s) and attenuation (A_s) required to achieve the desired amount of clutter rejection (C). A practical filter must also consider the number of multipliers or taps (N), passband ripple (R_p) and provide two transition regions (B_t) between the stopband and passband intervals. Unfortunately, the aforementioned design algorithm hereafter referred to as MPAR utilizes a relative error weighting parameter (W) in lieu of specifying values for R_p and A_s. Consequently, the design of a bandstop filter which achieves the desired clutter loss is largely a matter of trial and error as demonstrated in Table 1.

TABLE 1
MPAR DESIGN RESULTS
($N = 15$, $B_sT = 0.06$, $f_sT = 0.10$)

RUN	B_tT	W	R_p	A_s
1	0.03	1	3.1	15.0
2	0.03	10	7.2	28.1
3	0.03	20	7.8	33.5
4	0.05	20	2.5	43.0
5	0.04	20	4.5	38.0
6	0.04	10	4.2	32.5

The other filter design parameters are assigned the following values: $N = 23$, $B_sT = 0.06$, $f_sT = 0.1$ with a design goal of $C = 25$ dB which is to be achieved using $A_s \simeq 30$ dB and $R_p \simeq 5$ dB centered at 0 dB (unit gain). The value of R_p is selected to provide adequate target detectability throughout the passband. It is apparent that adjustments in B_t or W cause changes in both R_p and A_s and require several trials before achieving acceptable performance. Rabiner [4] has reported algorithms for iterating one particular MPAR design parameter until a desired error in the passband (D_p) or stopband (D_s) is achieved. These errors can be used to define A_s and R_p by

$$A_s = -20 \log (D_s) \qquad (1)$$

and

$$R_p = 20 \log [(1 + D_p)/(1 - D_p)] \qquad (2)$$

Although originally designed for lowpass filters, Houts and Burlage [1] successfully adapted the technique for the design of highpass filters to suppress ground clutter using B_t as the variable. The present extension of this philosophy to bandstop or bandpass filters is straightforward [5]. Because of the inclusion of a null at dc or 1/2T for even values of N, the application to bandstop filters is only practical for odd values of N and positive coefficient symmetry [6]. Although in the work which follows N is held constant, it should be recognized that increasing values of N provide larger A_s or smaller values of B_t or R_p, all desirable features for a filter. The response for a typical 23-tap bandstop filter designed using the aforementioned set of design parameters is shown in Figure 1 along with an ideal approximation to this filter which has uniform stopband attenuation and linear transition band response.

Clutter Rejection-Idealized Filter

A desired clutter rejection can be accomplished using some combination of the parameters A_s, B_s and B_t assuming the stopband is located at the clutter center, i.e., $f_s = f_c$. What is not clear is the best choice for each parameter. The tradeoff is readily determined for the idealized filter shown in Figure 1. The effect of increasing

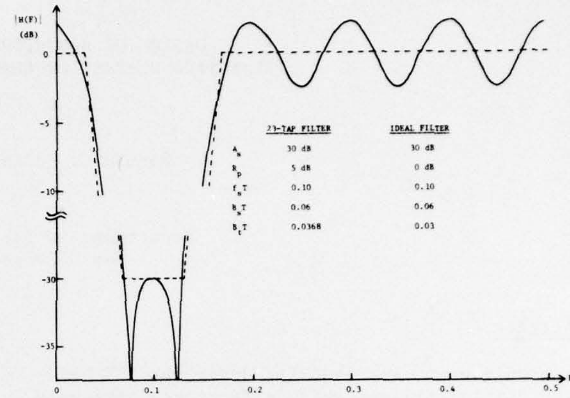

Figure 1. Frequency Response for FIR Bandstop Filter.

B_s for $B_t = 1.5\sigma$ is shown in Figure 2 for various choices of A_s. It follows that $C = 25$ dB can't

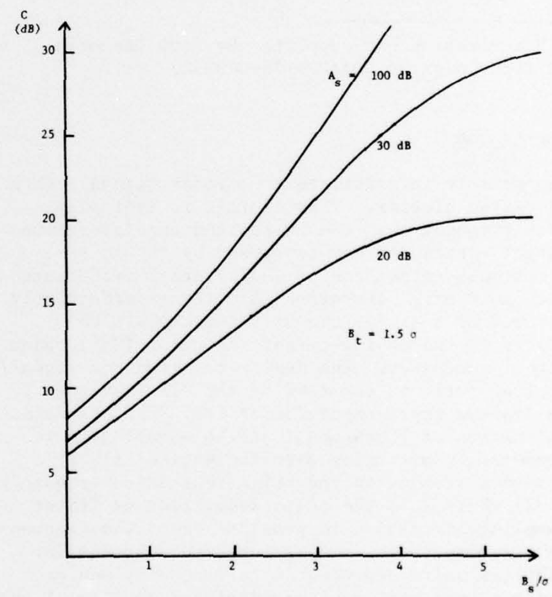

Figure 2. Effect of Stopband Attenuation on C-B_s Tradeoff.

be achieved for $A_s < 25$ dB and that it requires $B_s \simeq 4\sigma$ for $A_s = 30$ dB vs. 3σ for 100 dB. Of course a real filter design would require a much larger value of N for 100 dB attenuation than it would for 30 dB in order to retain $B_t = 1.5\sigma$. The effect of changing B_t is shown in Figure 3 for $A_s = 30$ dB. Again, it follows that $C = 25$ dB can be achieved either with $B_t = 2\sigma$, $B_s = 3.1\sigma$ or

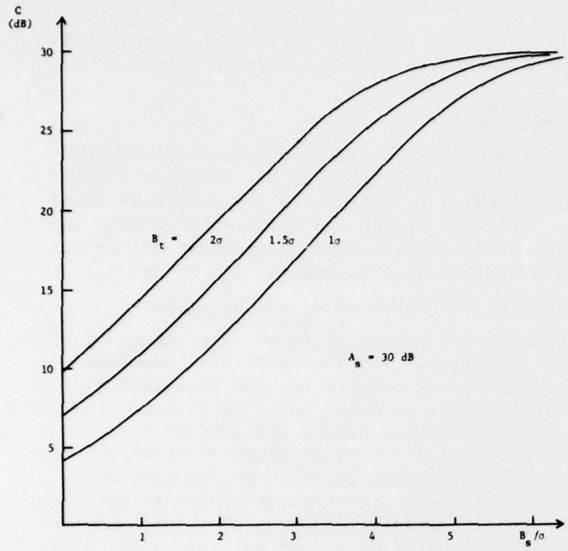

Figure 3. Effect of Transition Bandwidth on C-B_s Tradeoff.

$B_t = 1\sigma$, $B_s = 4.5\sigma$, however, the total unusable bandwidth (B) defined by

$$B = 2[B_s + 2B_t] \quad (3)$$

is 14.2σ in the first case and only 13.0σ in the second case. It is also evident that the wider transition widths (small N) play a significant role in clutter loss when the stopband is narrow ($B_s < 4\sigma$) and have a negligible effect when $B_s > 6\sigma$. The effect on clutter loss (C) of offsetting the clutter from the center of the stopband ($f_c \neq f_s$) is shown in Figure 4. The normalized frequency offset is defined as

$$\Delta f_c = |f_s - f_c|/f_s \times 100\%. \quad (4)$$

A ten percent frequency offset reduces C by 3 dB while a 20 percent offset costs 8 dB. Since it would be impractical to continuously match the filter to the changing average clutter velocity (v_c) it follows that the filter must be designed with more clutter rejection than needed under ideal conditions to protect against a change in v_c, e.g., a 10 dB margin permits a 25 percent change in v_c. Due to the symmetry of the filter and clutter spectrum the direction of velocity change is immaterial.

<u>Clutter Rejection - FIR Filter</u>

A series of 15 and 23-tap FIR bandstop filters were constructed using the transition bandwidth (B_t) as a variable parameter adjusted to meet the specifications $A_s = 30$ dB and $R_p = 5$ dB. A 15-tap

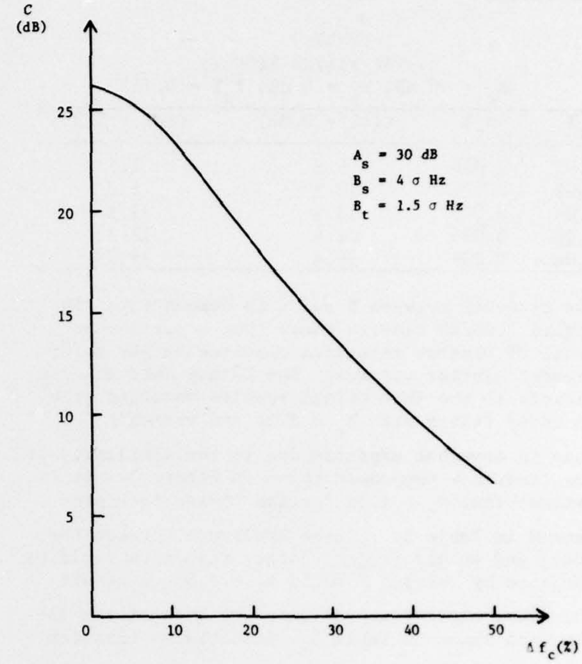

Figure 4. Effect of Frequency Offset on Clutter Loss.

filter was designed with $f_sT = 0.10$ and clutter rejection data is presented in Table 2 assuming Gaussian clutter with $\sigma T = 0.01$ or 0.02. The improvement is relatively constant for small B_sT (<0.04) which can be explained by noting that B_t is decreasing with increasing B_s in such a manner that the unusable bandwidth (B), defined by Equation (3), remains roughly constant. Furthermore, little additional clutter rejection is possible once $B_s > 4\sigma$.

TABLE 2
15-TAP FILTER RESULTS
(A_s = 30 dB, R_p = 5 dB, f_sT = 0.10)

B_sT	B_tT	C(σT = 0.01)	C(σT = 0.02)
0.00	0.052	22.3	13.6
0.01	0.048	23.3	13.8
0.02	0.043	25.6	14.4
0.04	0.068	27.1	21.5

Data for clutter rejection of a 23-tap filter is presented in Table 3 for $f_sT = 0.15$ and $\sigma T = 0.02$ or 0.03. Again C is less for the larger value of σ. What might appear surprising at first is to note that with $\sigma T = 0.02$, C is larger for a 15-tap filter than for a comparable 23-tap design. The explanation is that B_t is roughly 50% larger for the 15-tap design, hence a larger portion of the clutter spectrum experiences some attenuation. Naturally this is achieved at the expense of additional unusable

bandwidth.

TABLE 3
23-TAP FILTER RESULTS
(A_s = 30 dB, R_p = 5 dB, f_sT = 0.15)

B_sT	B_tT	$C(\sigma T = 0.02)$	$C(\sigma T = 0.03)$
0.00	0.030	6.9	3.7
0.02	0.029	10.3	5.8
0.04	0.040	18.5	11.1
0.06	0.036	22.4	13.2
0.08	0.031	26.4	15.0

The tradeoff between B and C is demonstrated in Figure 5 which clearly shows that a particular level of clutter rejection requires larger B for broader clutter spectra. The 23-tap data adheres closely to the theoretical results obtained from an ideal filter with $B_t = 1.5\sigma$ and variable B_s. This is somewhat expected due to the similarity of the frequency responses shown in Figure 1. It is evident that $B_t > 1.5\sigma$ for the 15-tap data presented in Table 2. Closer adherence between the ideal and actual filter clutter rejection could be obtained by varying N until $B_t = 1.5\sigma$, a result which was closely approximated by much of the 23-tap data shown in Table 3. Essentially identical

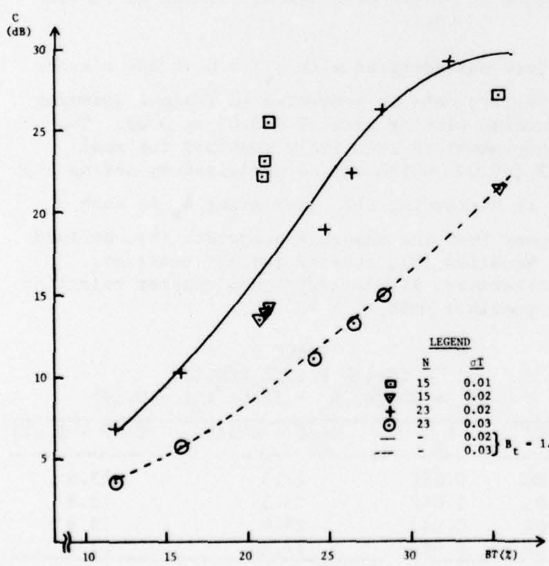

Figure 5. Clutter-Unusable Bandwidth Dependence on σT.

B_t results were obtained for a 23-tap filter designed with $f_sT = 0.1$. The effect of offsetting the clutter center frequency (f_c) from the center of the stopband was studied for two different 23-tap filters ($B_t \simeq 1.5\sigma$ and $B_s = 4\sigma$). For each study the clutter-loss data were equivalent to the theoretical results shown in Figure 4.

Conclusions

It is possible to achieve reasonable wideband clutter rejection with an FIR bandstop digital filter which is optimal in the Chebyshev sense. An idealized filter can be used to examine the clutter-unusable bandwidth tradeoff and select reasonable design values for A_s, B_s and B_t. If desired, the value of B_t can be adjusted by changing the number of taps. The amount of clutter rejection using 23-tap filters compares favorably with results for the idealized filter using similar stopband characteristics. Increased clutter rejection can be achieved by increasing the stopband width or stopband attenuation thus requiring larger N to maintain constant B. Additional investigations are required to select the center frequencies and numbers of bandstop filters required to effectively cover the wide range of possible clutter velocities. Although the filter design algorithm is not tied to the Gaussian power-density assumption, the idealized filter clutter-bandwidth tradeoff curves from which the filter design parameters are selected are dependent upon this assumption and would require recomputation for another clutter spectrum.

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